Neutron Star QPOs as Probes of Strong Gravity and Dense Matter

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Abstract. Millisecond X-ray time variability studies of accreting low-magnetic-field neutron stars in X-ray binaries probe the motion of matter in regions of strong gravity. In these regions, general relativity (GR) is no longer a small correction to the classical laws of motion, but instead dominates the dynamics: we are studying motion in strongly curved spacetime. Such millisecond X-ray variability studies can therefore provide unique tests of GR in the strong-field regime. The same studies also constrain neutron-star parameters such as stellar mass and radius, and thereby the equation of state (EOS) of ultradense matter. By comparing neutron star and black hole phenomenology the models can be constrained in unique ways. I discuss the prospects for mapping out space-time near accreting stellar-mass compact objects, and measuring the EOS of dense matter, through millisecond timing, particularly with an eye towards future missions. The key to further progress is timing sensitivity, and the overwhelming consideration for timing sensitivity is collecting area: contrary to most applications, the signal-to-noise ratio for the aperiodic timing phenomena produced by accretion flows increases *proportionally* with count rate rather than as the square root of it. A ten times larger instrument turns 1σ effects into 10σ effects (or does as well in 1% of the time). With the Rossi X-ray Timing Explorer (RXTE), using 0.6 m^2 collecting area, we have found several timing diagnostics from the accretion flow in the strong-gravity region around neutron stars and black holes. Next-generation timing instruments, larger in area by an order of magnitude and with enhanced spectral capabilities, are expected to turn these *diagnostics* of GR into true *tests* of GR. They are also expected to put strong constraints on neutron-star structure, and thereby on the EOS of supranuclear density matter.

1. INTRODUCTION

Neutron star QPO observations are reviewed in these proceedings by Swank, and neutron star QPO models by Miller; observations, models and prospects for black hole QPOs, which as I will discuss may well be closely related, are discussed by, respectively, Remillard, Abramowicz and Psaltis. My charge for the current paper is to discuss the question 'What are the most important and fundamental science issues that could be addressed by a next generation timing mission, with a focus on neutron star QPOs'.

The core issues addressed by the study of compact objects are fundamental: the nature of space and time, and the nature of matter. Specifically, the fundamental physics questions that we can address by studying accreting neutron stars and black holes in X-ray binaries, and, in the case of black holes, active galactic nuclei, relate to the issues of testing general relativity and determining the properties of ultradense matter. In the strong-field regime that applies near a compact object, classical physics fails, and general relativity has not yet been tested to any degree of confidence. Do black holes exist? This is not just an issue of interest to relativists but one

seen by many physicists as having much further-reaching consequences for, e.g., unification and the foundations of quantum mechanics (e.g., 't Hooft 2004). The astrophysical evidence is not yet strong enough to be universally accepted as sufficient proof for their existence and although 'proof' in the sense of proving the *absence* of certain properties will always remain elusive, it is also clear that we are still far away from the level of checking on black hole properties that could be obtained if we had one in the lab, and there are no fundamental obstacles preventing astrophysics getting *much* closer to that ideal. How does matter move in strong-field gravity? Is seems reasonable to say that we can use astrophysical measurements of matter accreting onto compact objects to map out the strongly curved spacetime that general relativity predicts surrounds them. What are the properties of matter at supra-nuclear density? In the neutron star case, the properties of the accretion flow constrain basic parameters such as mass and radius, and thereby (via stellar structure theory) the equation of state (EOS) of the ultradense matter at the star's core, whose properties are the subject of much speculation involving, among others, pion and kaon condensates, hyperons, and even strange matter (e.g., Heiselberg and Hjort-Jensen 2000).

It is important to note that millisecond time variability studies of accreting compact objects in X-ray binaries are not the only way towards these goals. Spectroscopy of the same accretion flows that produce the QPOs may evolve into a powerful probe of relativistic motion, and the synergy with timing will be enormous (§7). Active galactic nuclei (AGN) provide another window onto the same basic physical situation as in, and eventually should be understood within one common framework with, X-ray binaries (XRB). Gravitational waves, when detected, will probe general relativity in the self-gravitating regime, whereas XRB and AGN accretion flows probe the properties of the strong field in "vacuum". Eventually, black holes will be imaged at resolutions similar to the event horizon (nearly certainly in radio and infrared well before this happens in X-rays). Nuclear scattering experiments probe dense matter in the lab. Because the questions are so fundamental and important, clearly, several independent parallel approaches are desirable and if available, they should be followed.

X-ray timing of X-ray binaries is an approach that has several unique advantages. Because of the presence of either a neutron star or a black hole in these systems, nature is providing us with two sets of experiments, with one well-defined difference between them, for us to compare. We are observing the matter moving within a few kilometers, i.e., within the strong field gravity region, of these neutron stars and black holes, and since RXTE we are detecting signals *at* the dynamical time scales of these regions. While AGN have the advantage that we receive from them a larger number of photons per dynamical time scale, the photon fluxes are much higher for XRB, and for them it is easy to cover very large numbers of dynamical time scales (a hundred million per day), so that it is possible to reliably determine the *parameters* of the stochastic processes that characterize the time variability of the strong-field accretion flow rather than having to satisfy oneself with observing a particular *realization* of such processes.

The fundamental astrophysics question that needs to be addressed in the field of X-ray binary timing after RXTE in order to make progress with the core issues and fundamental physics questions summarized above might be formulated as follows: what is the nature of the millisecond signals that RXTE found in accreting low-magnetic field neutron stars and stellar-mass black holes? These signals occur at the dynamical time scale of the strong field region; are they indeed due to the motion of matter in the strong field region? This is nearly certainly so, in fact all models that have been proposed for the millisecond time variability agree about this. In this paper I discuss the questions that spring from this main one, and ways in which we might answer them, and use the result, with a next-generation timing mission: are we seeing the frequencies of *orbital* motion in the strong field region? Do we detect the frequencies of the general relativistic epicyclic motions associated with these orbits as well? How can we use these signals to constrain the mass-radius relation of neutron stars? What is the link with neutron star spin? What are the relations between the often strikingly similar timing phenomena observed in neutron stars and black holes?

2. ORBITAL MOTION

In the inner few kilometers of the accretion flow onto a compact object of mass M the accreting matter is moving close to the Schwarzschild radius at $R_S = 2GM/c^2$. The Keplerian orbital frequency at the general-relativistic innermost stable circular orbit (at radius $3R_S$ or $r_{ISCO} = 8.9\,\mathrm{km} \times (M/M_\odot)$) in a Schwarzschild geometry is $\nu_{ISCO} = 2192\,\mathrm{Hz} \times (M/M_\odot)^{-1}$. Kilohertz QPOs (Swank, these proceedings, van der Klis 2000 for reviews), discovered with RXTE in the X-ray flux of some 20 neutron-star LMXBs, with frequencies up to more than 1300 Hz and quality factors up to $\sim 10^2$, occur at these frequencies. Usually, two peaks are seen in the power spectra of the X-ray count-rate time series in the kHz domain (Fig. 1). Because the accretion disk is a wonderful source of periodicities by virtue of its Keplerian motion at each radius, and because kHz frequencies are those expected from the inner emitting region of the accretion disk around a low-magnetic field neutron star, it seems natural to identify quasi-periodic variability at such a frequency with orbital motion at a preferred radius in the inner disk. The most straightforward preferred radius is that of the inner edge of the Keplerian disk which in many descriptions is expected to be quite sharp (e.g., Miller, Lamb and Psaltis 1998). Indeed, as mentioned above nearly all detailed models that have been put forward to explain kHz QPOs identify the frequency of one or the other of the two peaks as the Keplerian orbital frequency at the inner edge of the disk. This, of course, is a very important conclusion, as it means we are directly observing orbital motion in strong gravity.

However, the evidence for the identification of (one of) the observed kHz QPO frequencies in terms of an orbital frequency is not yet iron-clad. Orbital motion could be empirically demonstrated with greater confidence by a number of different possible measurements: 1. independent measurements of frequency and orbital radius, where radius could be measured from continuum or line spectroscopy, demonstrating the predicted frequency - radius relation of orbital motion 2. measurements of orbital and epicyclic frequencies (§3) varying together in the way predicted by general relativity 3. measurements of the Doppler effect in an orbiting hot spot, 4. measurements of the orbital frequency ceiling predicted at the
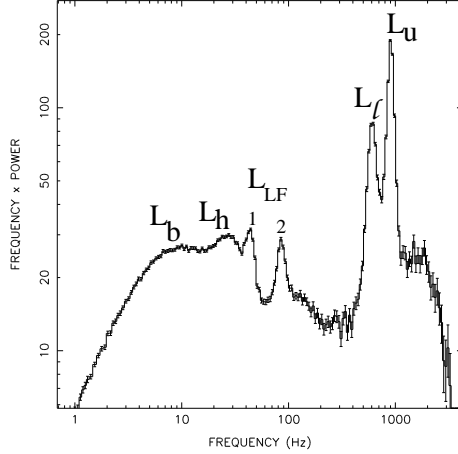
FIGURE 1. Power spectrum of Sco X-1 illustrating the multiple frequencies observed in the power spectra of neutron-star low-mass X-ray binaries.

ISCO, 5. detection of a beat-frequency relation (two frequencies precisely the spin frequency apart). Indications and approximate measurements for some of these possibilities have already been obtained.

High frequency orbital motion provides very direct constraints on mass, radius and angular momentum of the central compact object such that the hardest equations of state get rejected (see Miller, these proceedings); the higher the observed frequency, the stronger the constraint. As we shall see below, at high frequency the kHz QPOs become weaker as their frequency increases (Fig. 6), so more sensitive timing increases the highest observed frequencies and thereby tightens the limits on the EOS.

The kHz QPOs increase in frequency apparently when the instantaneous accretion rate through the inner disk $\dot{M}_d$ increases. In an orbital interpretation this implies that the inner edge of the disk (or other privileged radius in the accretion flow) moves inward when the frequency increases. The inner disk radius might vary between ~ 30 km for the lowest observed frequencies to less than 15 km for the highest frequencies (for a $1.4\,M_\odot$ neutron star; note that the innermost stable circular orbit (ISCO) from general relativity is located at ~ 12.5 km for such an object). One immediate prediction is that there should be a maximum on the observed frequency set by the ISCO, which may already have been observed (see Swank, these proceedings). In any case, assuming general relativity, such a maximum on the kHz QPO frequency is a very strong prediction of the orbital interpretation. With RXTE the QPOs become too weak to detect before the location where the ISCO expected is reached; with sufficient sensitivity we predict to see this in most sources.

3. EPICYCLIC MOTION

Both in neutron stars and in black holes we now know of a whole set of variable-frequency phenomena (Swank, these proceedings, Remillard, these proceedings) whose frequencies vary together in correlation with $\dot{M}_d$, as described above for the kHz QPOs. Models for these phenomena have been proposed that explain them in terms of orbital and general relativistic epicyclic motion (see Abramowicz, these proceedings) at preferred radii in the accretion disk that vary with accretion rate; for example orbital and epicyclic motion at the inner edge of the Keplerian disk whose radius r_{in} depends on $\dot{M}_d$ through the balance between gravitational, and radiative/magnetic stresses on the accreting material. If there is a way to express these frequencies into X-ray modulations, one preferred radius in the inner disk can already produce three non-commensurate frequencies. Of course, an accretion disk is a hydrodynamical flow, so while the particles in that flow each individually might have exhibited those three frequencies in their test-particle orbits, collectively their motions will be more complex, and combination frequencies as well as additional ones due to hydrodynamics (such as pressure waves) may occur and interact with these three basic GR epicyclic ones (e.g., Psaltis 2001). Stella and Vietri (1998, 1999), and Cui et al (1998) proposed, for, respectively, neutron stars and black holes, identifications of observed frequencies with the basic GR orbital and epicyclic frequencies. Certain low-frequency QPOs in neutron stars have a quadratic dependence on the frequency of the upper kHz QPO frequency (e.g., Psaltis et al. 1999) as predicted for the dependence of Lense-Thirring precession on orbital frequency. However, the putative Lense-Thirring precession frequencies are too high and the interpretation needs to be supplemented with an additional mechanism making only a harmonic of the actual Lense-Thirring frequency observable. Models of this type are usually called relativistic precession models even when the actual motions are not the test-particle-orbit precessional ones.
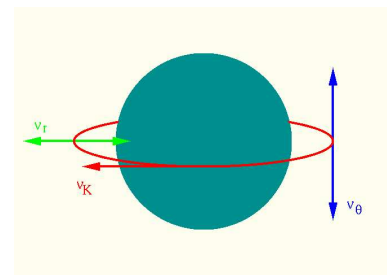

FIGURE 2. Azimuthal (v_K), radial (v_r) and meridional (v_θ) motion does not occur at the same frequency in general relativistic orbital motion, leading to epicyclic orbits.
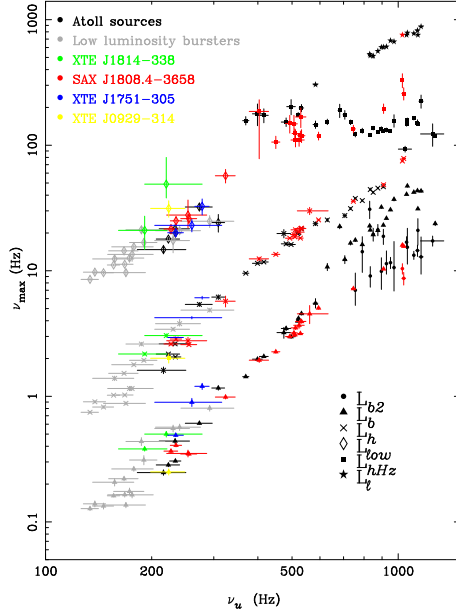
FIGURE 3. Measurements of various characteristic frequencies in power spectra of various types of low magnetic-field neutron stars plotted vs. the characteristic frequency of the upper kHz QPO. Note that most frequencies are variable and vary together, but that one seems to be approximately constant. From van Straaten et al. (2004); the frequencies for the millisecond pulsar SAX J1808.4-3658 were shifted by a factor 1.5 (see §5).

In addition to these variable frequencies there are indications, again both in neutron stars and in black holes, for QPOs with approximately constant frequencies. These are very important, as their approximate independence of $\dot{M}_d$ indicates they occur at frequencies set only by properties of the compact object, i.e., mass, angular momentum and perhaps magnetic field. This is suggestive of models relying heavily or exclusively on general relativity; a simple example would be the orbital frequency at the ISCO.

For the highest-frequency QPOs in black hole systems it is likely now that usually (but not always) we are looking at sets of harmonics (see Remillard, these proceedings). In some cases such possibly harmonically related peaks in black hole power spectra have been observed simultaneously, in a 2:3 frequency ratio (GRO J1655–40, Strohmayer 2001; XTE J1550–564, Miller et al. 2001). The reason that such a simple property is so hard to determine is that these QPOs are weak and therefore quite erratically detected, often strongly energy dependent, and the sources in which they occur transient. The impression one gets is that there may be a whole spectrum of frequencies just below our current detection limit; the same may be true for the neutron star systems. Kluzniak and Abramowicz (2001) suggest that it is relativity it-

self that picks out the preferred radii from the disk: they are the radii at which two of the three general-relativistic orbital and epicyclic frequencies have simple commensurabilities (2:3 ratios, etc.; Abramowicz, these proceedings). In their suggestion, at these radii a resonance occurs that amplifies exactly those frequencies among the wide range present in the disk, and makes them observable. This would mean that strong-field general relativity is exhibiting itself in pure form in these systems, displaying to us the frequencies preferred by gravitation theory from the multitude of frequencies in principle available from the hydrodynamical disk flow.

4. NEUTRON STAR SPINS

The neutron star spin provides an entirely independent source of frequencies available to the inner flow in case the compact object is a neutron star. Beat frequency models (see Miller, these proceedings) make use of this: in those models there is an interaction (mediated either by radiation or by the neutron star magnetic field) between the orbital frequency ν_{orb} at the inner edge of the disk and the spin frequency ν_s of the star. This leads to interaction frequencies such as $\nu_B = \nu_{orb} - \nu_s$, where ν_B is called the beat frequency. An approximate observed coincidence between the kHz QPO peak separation and the burst oscillation frequency (or half that frequency), interpreted as the neutron star spin frequency (Strohmayer, these proceedings) in several neutron star systems was the original motivation for models of this type.

The discovery of twin kHz QPOs separated by half the neutron star spin frequency (Wijnands et al. 2003; see figure 7 in Swank, these proceedings) in the first accreting millisecond pulsar (Wijnands and van der Klis 1998), the 2.5 millisecond period SAX J1808.4–3658 has completely transformed the landscape with respect to this class of models. The observation clearly demonstrates that a link between kHz QPOs and neutron star spin exists (for the currently known cases, the twin peak separation is near the spin frequency if the spin frequency is below 400 Hz, and near half the spin frequency if it is above 400 Hz), yet the set of frequencies observed in SAX J1808.4–3658 can not be produced by a beat frequency model as it has been understood up to now, one that operates by the kinematic interaction of two rotational (spin and orbital) frequencies to produce the beat frequency. Instead, the neutron star must by some interaction mode (presumably, through a magnetic or radiative pattern rotating with the spin) be forcing matter in the disk to move, in some way, in step with the spin. Models of this type have been proposed now by Lamb and Miller (2003) and by Kluzniak et al. (2003); in both models resonances occur in the disk flow between an

epicyclic frequency at a particular radius and the spin frequency. The models have a very different approach to making the observed frequencies variable over a sufficient range to match observations (via a beat interaction between a fixed and a variable radius in the disk in the Lamb and Miller description and via hydrodynamic effects in the flow tuning the frequency away from the resonance in the Kluzniak et al. case).

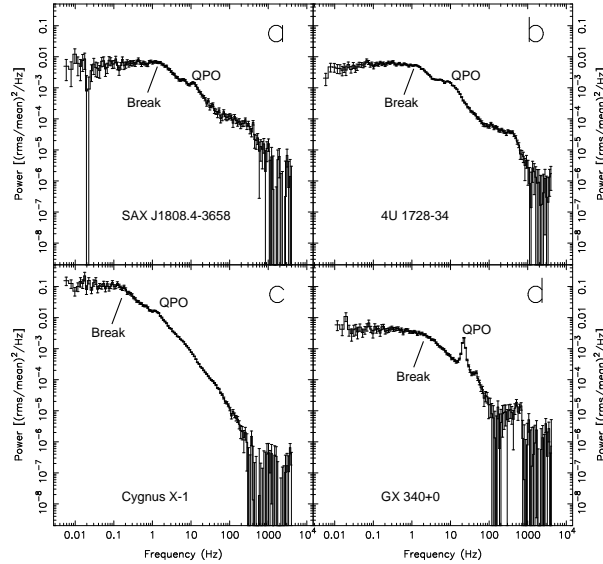## 5. SIMILARITIES BETWEEN NEUTRON STARS AND BLACK HOLES

FIGURE 4. Power spectra of various neutron stars and the black hole Cyg X-1. From Wijnands and van der Klis 1999.

The issue of whether we are seeing the same phenomena in neutron star and black hole systems is a very important one, as a phenomenon occurring in both types of system can not rely on any property unique to either type: the presence or absence of a solid surface, a horizon, a non-aligned magnetic field, spinning surface hot spots or frame dragging as strong as around near-extremal Kerr black holes can then all be excluded as ingredients for their formation. This leaves essentially only phenomena in the accretion flow (most likely the disk although there are other possibilities, e.g., a jet) for their explanation. The similarities in the timing properties between neutron stars and black holes are sometimes quite striking (van der Klis 1994a,b). The strong correspondence between the properties of low-luminosity X-ray bursters and black holes in the low state (e.g. Olive et al. 1998, Belloni et al. 2002; Fig. 4) certainly suggests to most experts that the same phenomena are seen. Even phenomena as apparently discrepant as the neutron star kHz QPOs and

black hole high-frequency QPOs might still be reconciled within a single theoretical description: the neutron star QPOs come in pairs with a separation related to the star's spin, have strongly tunable frequencies and low harmonic content, while the black hole ones are single, but with high harmonic content, and have a much more stable frequency. For example, the variable frequencies in neutron stars might occur because the phenomenon occurs at a variable (e.g., inner disk) radius, set by interaction of the disk flow with either a magnetic field or radiation from the stellar surface, while in black holes, in the absence of these influences, the same phenomenon occurs at a constant radius; the second QPO may occur only in neutron stars because it is due to an interaction with the spin; the high harmonic content in black hole QPOs may be due to relativistic effects (e.g, as a simple example, extreme Doppler boosting) on the flow and its emission that become important only near the ISCO.
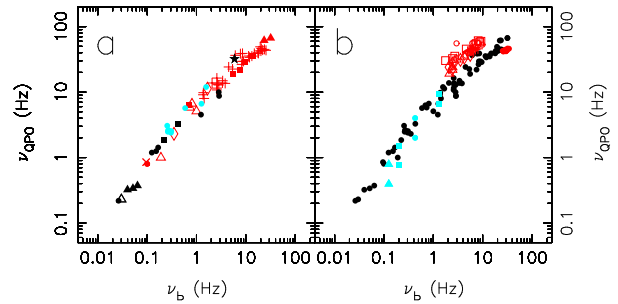

FIGURE 5. Frequencies of power spectral break and QPO as in Fig. 4 are well-correlated across neutron stars and black holes. From Wijnands and van der Klis 1999.

Similar frequency correlations are seen between phenomena covering a wide range in coherence and frequency in both neutron stars and black holes (e.g., Fig. 5 Wijnands and van der Klis 1999; also Psaltis, Belloni and van der Klis 1999, Belloni, Psaltis and van der Klis 2002). These correlations may even extend to accreting white dwarfs (in cataclysmic variables), as proposed by Warner and Woudt (2001). If so, then by similar reasoning as in the neutron star vs. black hole comparison no property unique to either type of object could be essential in producing the observed frequencies, which would exclude large-amplitude general-relativistic effects as a viable mechanism (orbital motion in the strong-field regime is still implied in the neutron star and black hole cases). It is good to keep in mind that these wide-ranging relations rely on identifying frequencies of different phenomena (QPOs as well as noise) with one another – eventually they need to be confirmed by detailed studies of the properties of these phenomena confirming that they *can* in fact be attributed to similar physical effects.

Such careful work has been reported at this meeting by van Straaten (these proceedings; Fig. 3), who has demonstrated that the QPO and noise frequencies of

atoll sources and low-luminosity bursters follow a universal scheme of correlations that can serve as a template against which to match the patterns of variability of other types of objects. The shifts, by a factor 1.5 in frequency, of the kHz QPOs in the millisecond pulsar SAX J1808.4–3658 as compared to all other atoll sources are very suggestive, and particularly in the context of the 2:3 frequency ratios observed in black hole high frequency QPOs suggest that similar, possibly resonant, phenomena occur in the accretion disks of these apparently very dissimilar systems. In view of the large similarities between low-magnetic field neutron star and black hole power spectra clearly the next step will be to try and put black hole frequencies into this universal scheme.

6. IMMEDIATE ASTROPHYSICS ISSUES

In order to address the fundamental astrophysics issues related to orbital and epicyclic motions, spin and the links between neutron stars and black holes described in the previous sections with the eventual aim, as decribed in §1, to address the fundamental issues to do with strong field gravity and ultradense matter we can see a number of immediate issues to address that all boil down to aspects of the question: what is the correct model for the millisecond variability phenomena? 1. How do neutron stars and black holes compare? We need to go beyond general statements of apparent similarity and difference to careful quantitative comparison; one approach was outlined at the end of the previous section. 2. What sets the frequencies? Are the frequencies related to radii in the disk, with variable frequencies arising at variable radii and constant frequencies at fixed radii in the disk? If so: 3. What picks out these radii? Are variable radii variable because they depend, through accretion disk physics, on the mass transfer rate through the disk, and is the relevant radius the inner radius of the Keplerian disk (within which the matter plunges in), set by radiative or magnetic stresses on the flow? Are constant radii set by compact object parameters (M, J, ν_s)? Do we see evidence for the ISCO? Do we see resonant radii in the disk? 4. What produces the X-ray modulation? How are the frequencies made observable as a modulation of the X-rays? Is it X-ray luminosity or the flux in our direction that is modulated? Are we looking at orbiting blobs, or is the accretion rate onto the compact object itself modulated in time? What decoheres the signals? Finite oscillation trains related to finite blob, vortex or loop lifetimes is only one possibility; frequency jitter, for example is another.

7. HOW TO ADDRESS THE ISSUES WITH A NEXT GENERATION TIMING MISSION

It is clear that with RXTE we have come a long way towards strong field gravity physics. We are seeing, and are able to study in some detail, variability at the dynamical time scale of the strong-field region in accreting low-magnetic field neutron stars as well as stellar-mass black holes and thus directly probing the matter flow in the strong-gravity region. The ISCO, and the three general-relativistic orbital and epicyclic frequencies explicitly figure in our models, and in fact most models only work thanks to strong-field gravity effects. We may have seen direct evidence for the ISCO already, and in any case there are strong predictions for its observable effects on known observable phenomena. Observed constant frequencies are likely due to phenomena that derive directly through GR from compact-object properties. The relativistic precession and the relativistic resonance models promise direct observational access to the three strong-field relativistic orbital frequencies, among which Lense-Thirring precession, which is a consequence of frame dragging. Even classical disk oscillation models (see Miller, these proceedings) involve orbital motion in the strong field region.

The aim of future timing instrumentation is to turn the *diagnostics* of strong field gravity and dense matter that we have found with RXTE into true *tests* of GR and *determinations* of the EOS. For this, we need to address the scientific issues outlined in the previous sections. The key to this is sensitivity. There are two ways in which we shall be able to make such progress with future instrumentation: (i) a much increased timing sensitivity thanks to a large (say, an order of magnitude larger than RXTE) collecting area, and (ii) the ability to combine millisecond timing information with sensitive spectroscopy with good resolution.

All signals discussed above are deep in the Poisson (counting statistics) noise, which means that they are difficult to characterize with precision, can only be detected over part of the range over which they occur, and that many are not seen at all. As it turns out, every physical model for the variability frequencies predicts its own set of parasitic, weaker frequencies in addition to the strong ones it set out to explain in the first place (e.g., Miller et al. 1998). These predicted patterns of weaker frequencies provide a strong test of each model. Searches for such weaker power spectral features are very difficult because this is really work at (or beyond) the limit of the sensitivity of current instrumentation, and the distinct impression of the observers is that there is much that is hiding just beyond current formal detection levels. However, success has been reached in a few instances: in three neu-

tron star systems an upper side band has been detected to the lower-frequency one of the twin kHz peaks (Jonker et al. 2000), in two or three black hole systems twin, instead of single, high-frequency QPOs have been detected (Strohmayer 2001, Miller et al. 2001, Remillard, these proceedings). These detections have led to only one claim in each case of a precise theoretical explanation (Psaltis and Norman 2002, Kluzniak and Abramowicz 2001), an unusual situation that testifies to the discriminating power of such additional frequencies, but far too few frequencies of this nature have been detected as yet for the full power of this method to be applied. With a next generation large-area timing instrument the entire "fingerprint" of the underlying phenomenon would be mapped out as a spectrum of interrelated frequencies which would make such explanations, if successful, unassailable, as of course they should be in order to be accepted as true tests of GR in the strong-field regime.

With respect to **timing sensitivity** it is important to realize, that the signal-to-noise ratio S/N (the "significance in σ's") for measuring weak aperiodic timing phenomena such as QPOs is given by

$$S/N = \frac{1}{2}Ir^2\left(\frac{T}{\Delta\nu}\right)^{1/2}$$

where I is the count rate (assuming negligible background), T the integration time, and r the fractional rms and $\Delta\nu$ the power spectral width of the signal (van der Klis 1989). This expression is valid for signals that can not be detected within their coherence time so necessarily $T \gg 1/\pi\Delta\nu$ (integration time much longer than signal coherence time), which is another way of saying that we consider power spectral features covering many power spectral bins; in this regime (thanks to the central limit theorem) the noise is Gaussian, so S/N levels are associated with the usual Gaussian probabilities. The expression implies that S/N is *proportional* to count rate and hence, for a similar spectral response, to collecting area A, rather than to $\sqrt{A}$ as is the usual case. Increasing the collecting area by a factor of ten implies that a 1σ effect changes into a 10σ effect (or that the same sensitivity can be attained in 1% of the time). For this reason alone there are incredible opportunities ahead for timing studies with a larger instrument.

A large area instrument will also open up an entirely new approach to millisecond timing studies, namely one where timing is combined with sensitive **spectroscopy**. Relativistically broadened Fe lines near 6.5 keV similar to those inferred in AGNs (e.g., Fabian 2000) exist in X-ray binaries as well (e.g., Miller et al. 2002, Parmar et al. 2002). These lines are successfully modeled as broadened and distorted by ordinary Doppler shifts, Doppler beaming, transverse Doppler effect (time dilation) and gravitational redshift, and diagnose the same
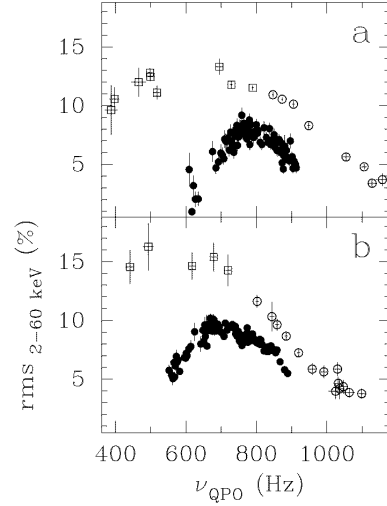

FIGURE 6. The amplitude of the kHz QPOs as a function of their frequency for (a) 4U 1728–34, (b) 4U 1608–52. Towards higher frequencies the QPOs disappear below the sensitivity limit. From Méndez et al. (2001).

strong-field region as millisecond timing. With relativistic lines it will be possible to combine the spectroscopic and timing diagnostics to enormously improve the grip we have on what is going on in the inner disk. To zeroeth order, the QPO frequency provides the orbital period, and the line profile the orbital velocity, so that we can solve for orbital radius r and central mass M. There are additional ways to determine these quantities, e.g.: M can also be determined from optical radial velocity measurements of the companion star, the gravitational redshift also depends only on M and r, the inner radius of the Keplerian disk can be constrained from the disk continuum emission. So, combining these measurements will provide strong tests of the models and shall certainly make it possible to prove (or disprove) that we are seeing orbital motion in the strong-field region.

Depending on details of instrumental implementation, with those much larger future instruments we shall be able to go further, and measure the line profile changes on short time scales, or equivalently the amplitude and phase differences between QPOs in several spectral bands within the line profile. The line widths are $\sim$keV, so moderate-resolution millisecond spectroscopy is sufficient to do this. Clearly, entirely different signals will be expected if the QPOs are caused by luminous blobs orbiting in the strong-field region and if they arise because the accretion onto the neutron star surface is being modulated at the QPO frequency: such measurements will then be able to decide the emission geometry and constrain the modulation model.
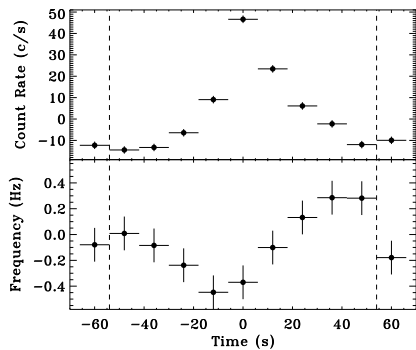
FIGURE 7. Light curve of milliHertz nuclear-burning oscillations (*top*) and associated kHz QPO frequency variations (*bottom*) in 4U 1608–52. The nuclear fueled X-ray flux from the neutron star surface makes the radius of the inner edge of the disk larger and thereby lowers the QPO frequency. This effect is *opposite* to that due to variations in accretion observed simultaneously, where flux increases make the frequency higher. From Yu and van der Klis (2002).

Because of the enormously enhanced timing sensitivity, the frequency range over which QPOs are detected will be considerably widened. Current observations are limited by the fall-off of QPO amplitudes towards the extreme frequencies (Fig. 6). It is likely that this will make it possible to follow kHz QPOs up to the ISCO and consistently see the predicted frequency saturation there, at the same time proving orbital motion, strongly constraining the EOS and providing a direct observation of a uniquely strong-field-GR effect; in relativistic precession models the two kHz peaks are predicted to coincide at the ISCO, so this will provide a strong test of the frequency model as well. The wider observable frequency range will also allow to test the different predictions of the various frequency models for the relations between the QPO frequencies (e.g., the quadratic dependence predicted for Lense-Thirring precession frequency or orbital frequency; the local maximum predicted in radial epicyclic frequency near the ISCO).

Measuring the patterns of weak related QPOs such as the full sideband patterns, and the weak harmonic patterns we are currently just able to glimpse in black holes will in a model-independent way test the neutron-star black-hole similarity, establish the reality of constant frequencies, and also, as already described above, provide conclusive tests of frequency models.

Finally, depending on the precise phenomenon, large area detectors will make it possible to detect the QPOs either within their coherence time $1/\pi\Delta\nu$ or even within one cycle $1/\nu$. This will open another plethora of possibilities, as this will allow to study them in the time domain. Then, it will for example be possible to perform

wave form studies and quantitatively constrain compact object mass, radius and angular momentum, orbital velocity and gravitational ray bending by modeling approaches such as described by Weinberg et al. (2001). A nice recent example of the power of time domain studies that do not require any modeling is provided by the recent work by Wenfei Yu (Yu and van der Klis 2002) on the milliHertz nuclear-burning oscillations in 4U 1636−53, which shows beautiful evidence for the nuclear X-ray flux pushing the inner disk out and lowering the kHz QPO frequency (see Fig. 7).

Clearly, the prospects for doing strong field gravity and dense matter physics by timing X-ray binaries with large area detectors are simply tremendous. RXTE has given us the signals from the strong-field region; what we need now is an instrument to exploit the opportunities they present.

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